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ON THE MERIDIONAL DISTRIBUTION OF SOURCE AND SINK TERMS OF THE KINETIC ENERGY BALANCE [1, 2]

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ABSTRACT

The latitude-height distributions of the kinetic energy generation and dissipation over North America are presented in a series of cross sections from 25° to 70° N. and from the surface to the 50-mb level. The generation was computed using the twice-daily observed wind and geopotential data for a 1-yr period. The dissipation was obtained for a 3-mo summer period as the residual term of the kinetic energy equation. Throughout all latitudes, the generation and dissipation have a maximum in the planetary boundary layer. They gradually reach a minimum in the mid-troposphere, then increase to another maximum at the jet stream level except in middle latitudes. In the upper troposphere, there seems to be a characteristic meridional distribution both for generation and dissipation. The generation is significantly large north and south of the middle latitude where the kinetic energy is adiabatically destroyed. Those latitudes of large generation in the upper troposphere are also characterized by high frictional dissipation values. Reference is also made to the results in available numerical experiments for comparison and discussion.

1. INTRODUCTION

One phase of our observational study of the kinetic energy balance has been concerned with the vertical distribution of the source and sink terms (e.g., Kung 1969). It has been shown that there are two maxima of the generation and dissipation in the planetary boundary layer and at the jet-stream level. These studies also may imply that the intensity of the atmospheric general circulation is significantly higher than is being assumed in most of the numerical models.

The area mean values of energy variables over the North American Continent for 20 pressure layers from the surface to 50 mb were examined in detail in our previous reports (Kung 1966*a*, 1966*b*, 1967, 1969). One resulting interest then concerns the meridional distribution of energy variables, especially that of the generation and dissipation which represent source and sink terms, respectively, in the kinetic energy balance. As our study progresses, the present degree of refinement in the analysis scheme allows us to examine some interesting results in that regard.

In this paper, the meridional distributions of generation and dissipation are studied over the North American region from 25° to 70° N. for the same 1-yr period from January 1962 through January 1963 as for our preceding report (Kung 1969). As in our previous reports (loc. cit.), the data source was the Massachusetts Institute of Technology (MIT) General Circulation Data Library (NSF Grants GP–820 and GP–3657). The computation was performed for each 50-mb pressure layer from the surface to the 50-mb level in each 5° latitudinal zone. The generation from the work done by the horizontal pressure force and the dissipation, which was obtained as the residual term of the kinetic energy equation, will be presented in latitude-height cross sections and discussed in terms of the observational study.

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2. KINETIC ENERGY EQUATION AND SCHEME OF ANALYSIS

The balance requirement of the kinetic energy over an area can be expressed by

$$E=-\frac{\partial k}{\partial t}-\frac{1}{A}\oint_c \mathbf{V}k\cdot\mathbf{n}ds-\frac{\partial\omega k}{\partial p}-\mathbf{V}\cdot\nabla\phi$$

where $\partial k/\partial t$ is the local change of the kinetic energy; $\frac{1}{A}\oint_c \mathbf{V}k\cdot\mathbf{n}ds$, the horizontal outflow; $\partial\omega k/\partial p$, the vertical transport; and $-\mathbf{V}\cdot\nabla\phi$, the generation, with the residual term E then being the frictional dissipation. While $\frac{1}{A}\oint_c \mathbf{V}k\cdot\mathbf{n}ds$ refers to the area mean of the flux divergence of kinetic energy $\nabla\cdot\mathbf{V}k$, the remaining terms in the above equation are area mean values. A and s are the area and its boundary, $\mathbf{n}$ is the vector normal to s, and other symbols are those of the standard hemispherical polar coordinate (x, y, p, t) system. Refer to the previous reports (loc. cit.) for a discussion of the above equation.

The method of computing the terms on the right side of the equation was essentially the same as described in the preceding report (Kung 1969). However, it was necessary to modify the computation scheme to suit the purpose of this analysis. A sensitive quantity such as $-\mathbf{V}\cdot\nabla\phi$ is computed more reliably over a larger area of the radiosonde observational network. As the area mean value was estimated over the latitudinal zones in this study rather than over the whole of North America as in previous studies, certain care must be taken. The term $-\mathbf{V}\cdot\nabla\phi$ was computed for individual observational stations (Kung 1966*a*). Computed values were then tested by performing the same computation for the same stations with a few surrounding stations omitted for each individual station

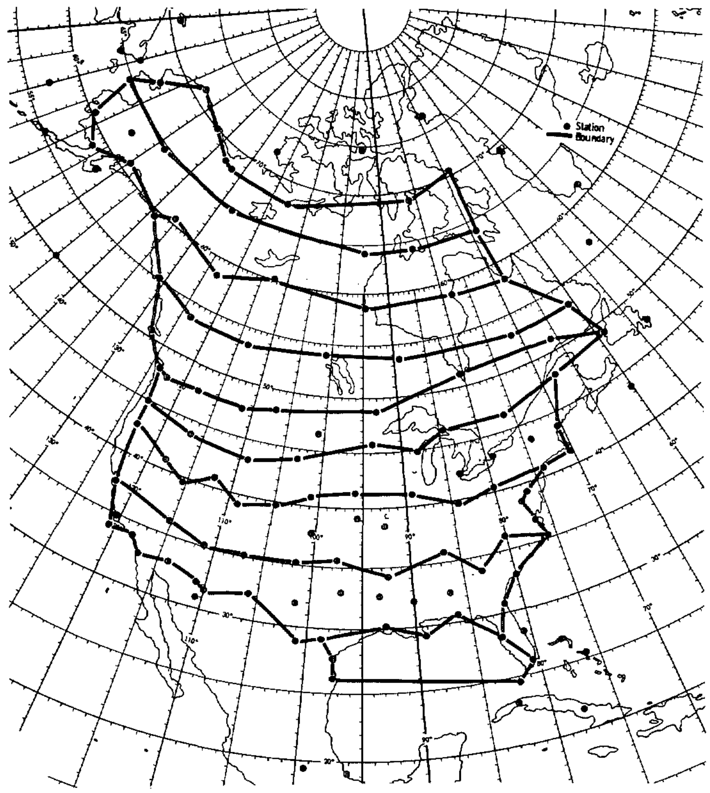

FIGURE 1.—Latitudinal zones and aerological stations.

whenever possible. The station values of $-\mathbf{V}\cdot\nabla\phi$ that showed inconsistency in such a comparison were rejected.

Figure 1 shows the network of the rawinsonde/radiosonde observations used in this study from the MIT General Circulation Data Library (see section 1). A total of 134 stations are involved. As shown in the figure, nine latitudinal zones of approximately 5° width from 25° to 70° N. are specified by connecting the appropriate stations. The 23 stations outside all of these nine latitudinal zones were used only to compute $\nabla\phi$ for other stations. The $\frac{1}{A}\oint_c \mathbf{V}k\cdot\mathbf{n}ds$ was computed as the line integral along the boundary of each latitudinal zone. The $\partial k/\partial t$, $\partial\omega k/\partial p$, and $-\mathbf{V}\cdot\nabla\phi$ were computed for each individual station; the area mean values of those terms were then obtained for each 50-mb pressure layer from the surface to the 50-mb level for each latitudinal zone. The dissipation E was then derived as the residual term to balance the kinetic energy equation. The computed values for a station located on the boundary between two neighboring zones were utilized twice in estimating the area mean values of both neighboring zones. To a certain degree, this may be regarded as a smoothing process for computed variables except $\frac{1}{A}\oint_c \mathbf{V}k\cdot\mathbf{n}ds$.

The twice-daily wind and geopotential observations at 00 and 12 GMT over the above network were used. The period of computation covered the 1-yr period from January 1962 through January 1963. Due to difficulties in the data tapes in our possession, December 1962 data were not used. As in the preceding report (Kung 1969), throughout this paper the winter 3-mo value is the average of the computed daily values of January 1962, February 1962, and January 1963; the summer 3-mo value of June, July, and August 1962; the winter 6-mo value of January, February, March, April, and November 1962 and January 1963; and the summer 6-mo value of May, June, July, August, September, and October 1962. The annual mean is obtained as the average over the entire 12 mo.

3. THE SOURCE TERM

The generation $-\mathbf{V}\cdot\nabla\phi$ represents the source term in the kinetic energy balance. Although the term $-\mathbf{V}\cdot\nabla\phi$ must be positive as a global average for a reasonable length of time to maintain the general circulation against the frictional dissipation, it is expected to vary from place to place and from time to time, even changing the sign (Lorenz 1967 and Soong and Kung 1969). In our previous studies (loc. cit.), the area mean value of $-\mathbf{V}\cdot\nabla\phi$ over the North American Continent showed a characteristic vertical distribution with maxima in the planetary boundary layer and at the jet-stream level, which seems to be a characteristic global feature as indicated in the numerical experiments of the Geophysical Fluid Dynamics Laboratory (GFDL) model (Smagorinsky et al. 1965 and Manabe et al. 1970). Thus it is pertinent to see if our present study shows some meaningful meridional distribution of this source term over the North American region.

The latitude-height cross section of annual mean $-\mathbf{V}\cdot\nabla\phi$ values for the average of 00 and 12 GMT observations is presented in figure 2. The general features observed in this figure are interesting, especially in comparison with the numerical experiments with the GFDL model (loc. cit.). Throughout all latitudes from 25° to 70° N., $-\mathbf{V}\cdot\nabla\phi$ is positive in the lower troposphere with the maximum at the lower boundary. In the mid-troposphere, the generation is generally weak. However, in the upper troposphere, the latitudinal alinement of the $-\mathbf{V}\cdot\nabla\phi$ values shows a characteristic meridional variation. In this part of the atmosphere, we have significantly large positive $-\mathbf{V}\cdot\nabla\phi$ values north and south of the middle latitudes, namely, approximately north of 55° N. and south of 40° N., while the middle-latitude region is characterized by negative values of $-\mathbf{V}\cdot\nabla\phi$. A negative value should mean adiabatic destruction of kinetic energy by motion of the atmosphere against the pressure gradient force, which in turn implies the conversion of the kinetic energy into the available potential energy.

This meridional variation of $-\mathbf{V}\cdot\nabla\phi$ is in good qualitative agreement with the numerical results of the GFDL model experiments (loc. cit.). Especially noteworthy is the very close agreement on the position of the middle-latitude negative region in the upper troposphere between our observational study and the GFDL experiment (Smagorinsky et al. 1965). Our observational finding of two intense generation areas at the jet stream level to the immediate north of the negative region and at the location of the subtropical jet is also in agreement with the 1965 GFDL model experiment.

In addition, we observe in figure 2 another intense generation area in the upper troposphere around 25° N. with indication of its extension farther south. This was

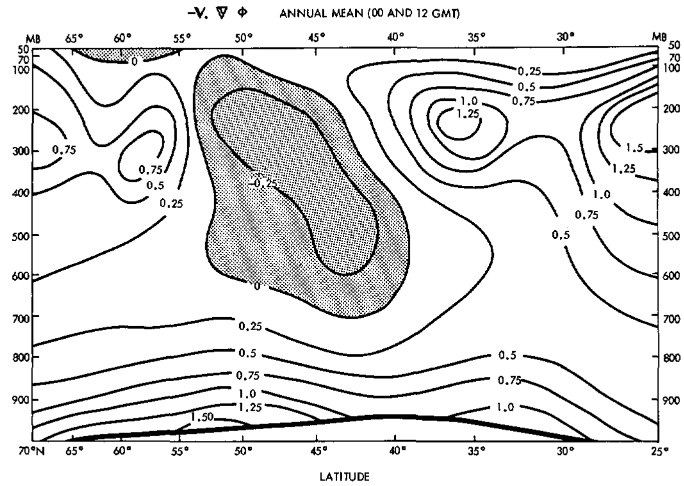

FIGURE 2.—Latitude-height cross section of the annual mean kinetic energy generation $-\mathbf{V}\cdot\nabla\phi$ in units of watts m^{-2} per 50 mb (average for 00 and 12 GMT).

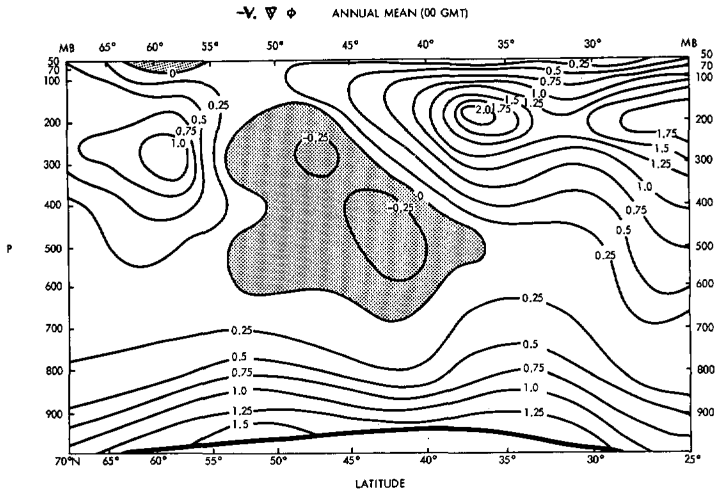

FIGURE 3.—Same as figure 2, except for 00 GMT.

not evidenced in the 1965 GFDL experiment, but may be compared with the 1969 GFDL model experiment with a hydrologic cycle (Manabe et al. 1970). In the 1970 GFDL experiment, the combined effect of the conversion of eddy potential energy into kinetic energy and the pressure interaction term should indicate a maximum of $-\mathbf{V}\cdot\nabla\phi$ near 300 mb, or a little above, in the equatorial zone. This maximum may correspond to our southernmost maximum in figure 2. However, we note the appearance of our maximum at 25° N. rather than in the Tropics as in the GFDL experiment. As shown in figure 1, the number of observational stations in the latitudinal zones of 25°–30° N. and 65°–70° N. is rather limited; thus it is possible that this southernmost maximum is merely an isolated local phenomenon. On the other hand, it is not surprising that this tropical phenomenon appears north of the global average position in the particular region of our observational data.

There seems to be a significant diurnal variation of $-\mathbf{V}\cdot\nabla\phi$ as discussed in the preceding report (Kung 1969) and more recently by Gray (1970). The annual mean latitude-height cross sections of $-\mathbf{V}\cdot\nabla\phi$ for the 00 and 12 GMT observations are presented separately in figures 3 and 4. It is apparent that the generation rate is significantly higher for 00 GMT than for 12 GMT in most parts of the atmospheric cross section. Though not presented here in a separate figure, it should be noted that the diurnal variation is particularly significant during summer. Further study on this subject will be interesting if we compute $-\nabla\cdot\mathbf{V}\phi$, $-\partial\omega\phi/\partial p$, and $-\omega\alpha$ separately and examine their diurnal variation along with that of $-\mathbf{V}\cdot\nabla\phi$.

Figures 5 and 6, respectively, show the latitude-height cross sections of winter and summer 3-mo means of $-\mathbf{V}\cdot\nabla\phi$ for the average of 00 and 12 GMT observations. The features shown in these figures generally conform to the pattern of the annual mean cross section in figure 2.

To summarize the preceding discussions concerning the meridional distribution and diurnal and seasonal variations of $-\mathbf{V}\cdot\nabla\phi$, the vertically integrated kinetic energy

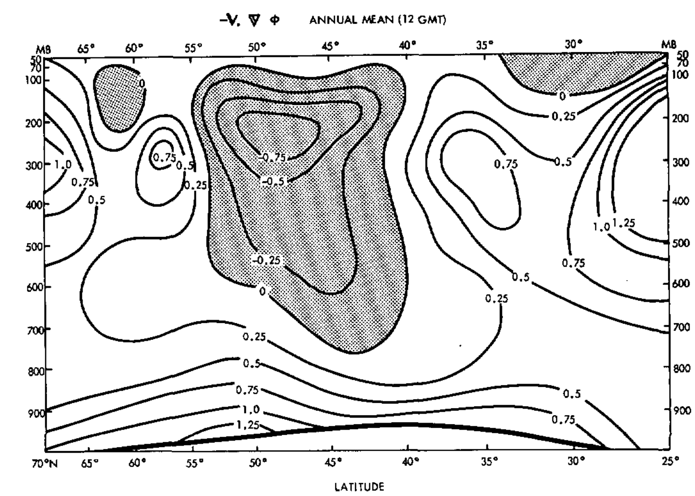

FIGURE 4.—Same as figure 2, except for 12 GMT.

generation $-\mathbf{V}\cdot\nabla\phi$ from the surface to 50 mb is listed separately in table 1 as winter 6-mo, summer 6-mo, and annual means.

The estimate of kinetic energy generation essentially depends on the magnitude of the cross-isobar flow or the ageostrophic components of the observed wind. If the latitude-height cross section of $-\mathbf{V}\cdot\nabla\phi$ shows a characteristic pattern as discussed above, we may expect it to be reflected on the distribution of ageostrophic wind components. As an example, the ageostrophic departure of the zonal wind component $(u-u_g)$ for the summer 3 mo is shown in the latitude-height cross section of figure 7. Comparing this figure with figure 6, the corresponding summer 3-mo generation, we see that the generation in the lower troposphere and in the region of the jet stream can be generally associated with the areas of strong subgeostrophic departure, and the generation to the north of the jet stream region can be identified with super-geostrophic departure. The distribution of the ageostrophic zonal wind component is consistent with Smagorinsky's (1963) two-level model experiment and also with Holo-

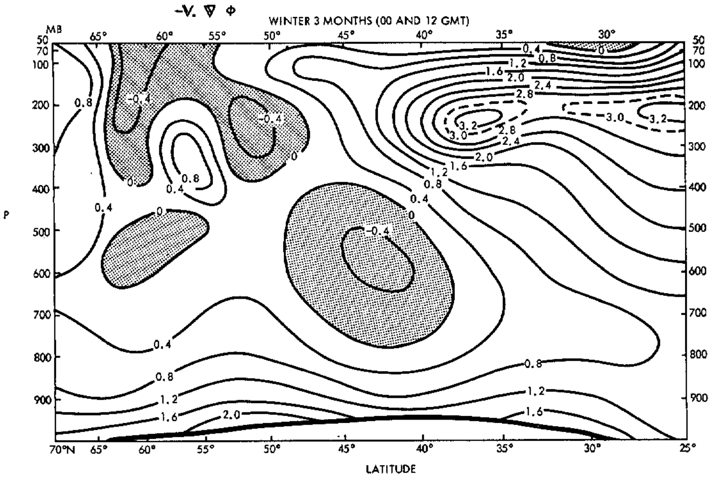

FIGURE 5.—Latitude-height cross section of the kinetic energy generation $-\mathbf{V}\cdot\nabla\phi$ for 3 winter mo in units of watts m^{-2} per 50 mb (00 and 12 GMT).

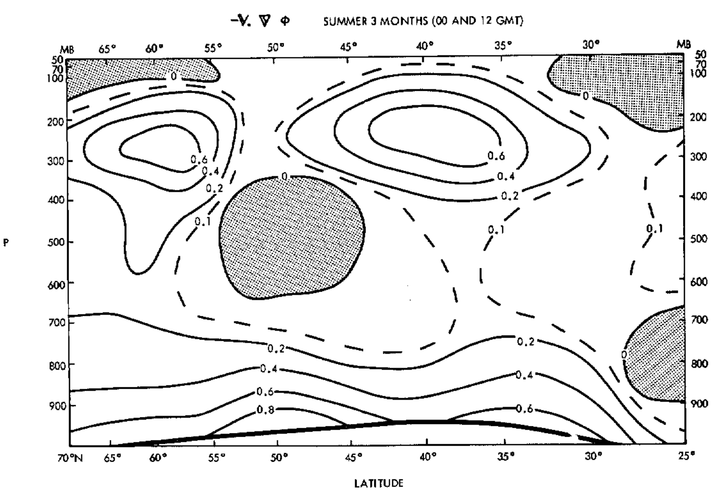

FIGURE 6.—Same as figure 5, except for 3 summer mo.

TABLE 1.—*Vertically integrated kinetic energy generation* $-\mathbf{V}\cdot\nabla\phi$ *from the surface to 50 mb in each latitudinal zone (degrees north) in units of watts* m^{-2}

	70°–65°	65°–60°	60°–55°	55°–50°	50°–45°	45°–40°	40°–35°	35°–30°	30°–25°
Winter 6 mo									
00 GMT	7.39	7.14	10.84	4.88	2.76	2.01	17.18	16.63	28.99
12 GMT	15.76	2.06	6.76	5.24	1.70	1.26	13.71	16.52	30.69
Mean	11.58	4.60	8.80	5.06	2.23	1.63	15.44	16.57	29.84
Summer 6 mo									
00 GMT	10.93	12.72	9.30	6.05	5.35	4.57	10.19	5.44	2.93
12 GMT	7.21	8.24	8.38	−1.33	−5.70	−4.90	0.63	−1.79	−1.96
Mean	9.07	10.48	8.84	2.36	−0.17	−0.16	5.41	1.83	0.49
Annual									
00 GMT	9.16	9.93	10.07	5.47	4.05	3.29	13.68	11.03	15.96
12 GMT	11.48	5.15	7.57	1.95	−2.00	−1.82	7.17	7.36	14.36
Mean	10.32	7.54	8.82	3.71	1.03	0.74	10.43	9.20	15.16

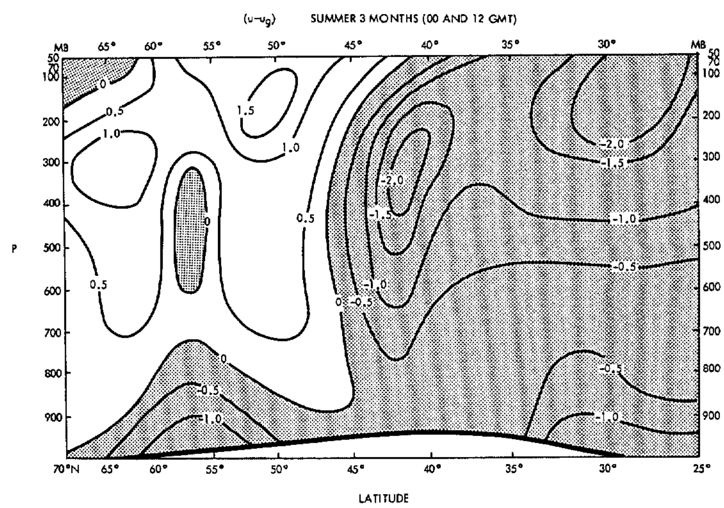

FIGURE 7.—Latitude-height cross section of the ageostrophic zonal wind component $(u-u_g)$ for 3 summer mo (00 and 12 GMT).

painen's (1966) evaluation of ageostrophic departure of the mean zonal wind.

We have described the latitude-height distribution of $-\mathbf{V}\cdot\nabla\phi$ as the source term from the viewpoint of the kinetic energy balance as expressed in the equation at the beginning of the preceding section. Further investigation of the mechanism involved in this generation term will require detailed breakdown of the kinetic energy equation. It is noteworthy that a comprehensive study was recently carried out concerning the maintenance of the mean zonal kinetic energy by Starr et al. (1970).

4. THE SINK TERM

As pointed out in our previous reports (loc. cit.), it is a useful independent measurement to obtain the dissipation value as the residual term E of the kinetic energy equation, since virtually no censensus exists in regard to the dissipation mechanism. Using the area mean E values over North America, our previous reports have shown that the dissipation is at a maximum in the planetary boundary layer, decreases gradually to a minimum in the mid-troposphere, and then increases again to the second maximum at the jet-stream level. It will be highly informative if we can examine the meridional distribution of dissipation along with generation. However, a few comments concerning the nature of E obtained as the residual term will be pertinent before presenting some of our results.

The dissipation E derived as the residual term of the kinetic energy equation with large-scale synoptic data is the sink term of the large-scale kinetic energy balance. One convenient way to discuss the energetics of the general circulation is to treat the kinetic energy of smaller scale motions as a portion of the internal energy (Lorenz 1967), thus effectively isolating the problem of the subgrid scale dissipation processes from he discussion. At present, we may conveniently presume that E is the kinetic energy removed from the grid scale for eventual viscous dissipation. The presumption is open to question. However, it will not materially affect our presentation in this section, as we treat the dissipation E essentially as the sink term in the large-scale kinetic energy balance.

If E is integrated over the total mass of the atmosphere, it must have a positive value. When E is evaluated for a

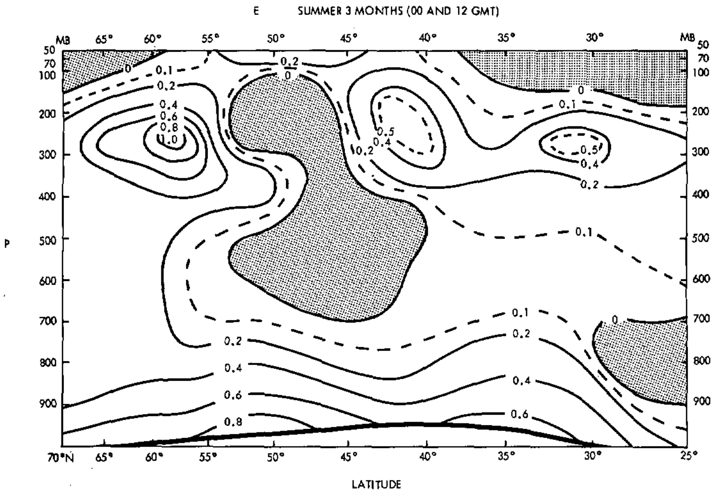

FIGURE 8.—Latitude-height cross section of the kinetic energy dissipation E for 3 summer mo (00 and 12 GMT).

portion of the atmosphere, however, it is not necessarily always positive locally. This is because E represents $\mathbf{V}\cdot\mathbf{F}$, where $\mathbf{F}$ is the vector of the frictional force, and it includes the boundary work term along with the local dissipation value. While the boundary work term is expected to be negligible for the volume of atmosphere over which we are integrating E, we may still have a slight negative E where the dissipation is weak. Also, since we cannot detect energy-generating subgrid scale eddies with large-scale synoptic data, we might have underestimated $-\mathbf{V}\cdot\nabla\phi$. This could be a contributing factor to some slight negative E values locally.

Our previous reports (loc. cit.) indicated a significant diurnal variation in the residual term E corresponding to that in the generation $-\mathbf{V}\cdot\nabla\phi$. While there seems to be a significant diurnal variation for $-\mathbf{V}\cdot\nabla\phi$ as discussed in the preceding section, the diurnal variation of the dissipation is interesting as well as puzzling. One possible explanation for this is the failure in estimating the local change $\partial k/\partial t$, thus biasing the estimate of dissipation as the residual term. As we have only two observations daily and $\partial k/\partial t$ estimated for a 24-hr interval is negligibly small, the diurnal variation of kinetic energy cannot be correctly taken into account for the balance requirement. For this reason, the residual term for the average of 00 and 12 GMT observations is taken as the dissipation. If the diurnal variation is the dominant variation during the course of a day, then E for the average of 00 and 12 GMT should be a good estimate of the average dissipation. Although we expect the existence of a secondary semidiurnal variation from data available in the literature (e.g., Finger et al. 1965), we may expect its effect on the magnitude of $-\mathbf{V}\cdot\nabla\phi$ and thus on E to be minor for the portion of the atmosphere we are investigating. It is noteworthy that recently Gray (1970) pointed out the feasibility of significant diurnal variation of the dissipation by assigning the cumulus activities as the possible mechanism for this term.

The horizontal outflow of kinetic energy $\frac{1}{A}\oint_c \mathbf{V}k\cdot\mathbf{n}ds$ from the area is a difficult term to evaluate when the wind is strong and where the area is small (Kung 1966*b*, 1969). When the wind is strong during the winter, the error components in wind observations accumulate in k. The direct use of wind data at stations on the area boundary to obtain the line integral is a problem particularly for a small area such as the latitudinal zones in this study during the winter, since the outflow term is large and errors in its estimation significantly affect the residual term E. Our careful editing of the daily computations confirms that the outflow computed for a latitudinal zone during the summer 3 mo is a rather small and stable quantity, and we can present the dissipation E with a certain degree of confidence. For this reason, the dissipation value for this season only is presented in this paper.

Figure 8 shows the latitude-height cross section of the dissipation for the 3 summer mo for the average of 00 to 12 GMT observations. Though not presented here, the cross sections for other seasons are about the same as that of summer in figure 8 except that we tend to underestimate the E value at the jet-stream level because of a seemingly spurious overestimate of the outflow term for individual latitudinal zones.

As we expect, there is a first maximum of the dissipation in the planetary boundary layer. Latitudinally, there are two maxima of the boundary layer dissipation near 50° and 35° N. The numerical value and latitudinal variation of the boundary layer dissipation in figure 8 indirectly obtained from the balance requirement of kinetic energy are in close agreement with the author's (1963) earlier estimate of the boundary layer dissipation using Lettau's (1962) boundary layer model.

The dissipation reaches a minimum at the mid-troposphere and then increases upward to the second maximum at the jet-stream level except at the middle latitudes, generally conforming with what we observed in the vertical distribution of the area average of E for the whole continent (see previous reports, loc. cit.).

The latitudinal variation of the dissipation in the upper troposphere as presented in figure 8 is interesting. There is a slight negative E area between 45° and 55° N. at the jet stream level, which may better be regarded as a minimum dissipation area according to our discussions above. North and south of this E area, we observe clear maxima of E at the jet stream level. Although the data coverage in the 25°–30° N. zone was limited, the area of the upper troposphere dissipation seems to extend to the tropical region with its lower boundary extending to the middle troposphere. This is in qualitative agreement with the 1969 GFDL model experiment (Manabe et al. 1970) and Ellsaesser's (1969) climatological estimate with upper wind statistics. The dissipation pattern in figure 8 also seems to agree with Charney's (1969) suggestion concerning the upper troposphere dissipation in the Tropics.

There is a notable discrepancy between the latitude-height cross section in figure 8 and that obtained in the GFDL model experiments (Smagorinsky et al. 1965 and Manabe et al. 1970). In the upper troposphere, we have a minimum E region between maxima at its north and south;

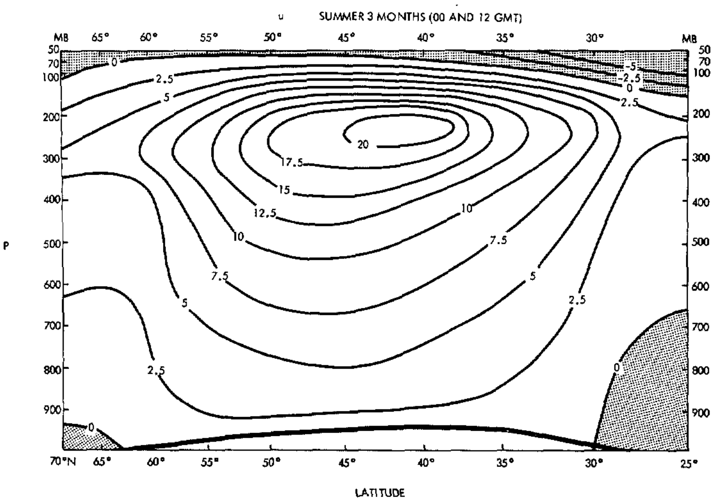

FIGURE 9.—Latitude-height cross section of the zonal wind component u for 3 summer mo (00 and 12 GMT).

but in the GFDL experiments, this is the area where they have the upper troposphere dissipation maximum. Our outflow term was computed with the observed large-scale synoptic data, and it showed a small flux divergence rather than convergence for that part of the atmosphere, thus resulting in the minimum (actually slightly negative) dissipation there. Apparently, the problem cannot be settled at this point.

The latitude-height cross section of u for the summer 3 mo in figure 9 is presented in connection with that of E in figure 8. However, since our data coverage in space and time is rather limited, along with our inability to directly measure the subgrid scale diffusion, discussion in that respect would be premature.

5. REMARKS

The results reported in this paper were based on a rather limited amount of observational data. Spatially, the study covers only the North American region; and in time, it covers only a 1-yr period. The study of the sink term is only presented on the basis of data over a 3-mo period. Therefore, the presentation and discussion in this paper must be regarded as tentative and limited. Nevertheless, the comparison of our tentative observational results with the hemispherical numerical experiments enables us to present interesting discussions concerning the kinetic energy balance of the atmosphere. Currently, an extensive improvement of our computational method, which will allow us to examine the problem on a firmer basis, is underway.

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